Shaping the central structure in CDM halos

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Abstract. Coupling the dark matter (DM) and baryonic components in galaxies via dynamical friction (by allowing the latter to be clumpy) leads to energy input into the DM. The resulting expanding tendency in the DM component overcomes the competing effect of adiabatic contraction, resulting from the shrinking gas component, and leads to a nearly constant density core. The baryonic mass inflow also leads to the coupling of the structure at the kpc scale and below and that of the structure of the DM at the 10 kpc scale and above, with rate of mass inflow being dependent on the initial halo central concentration. The latter also determines the final halo core radius.

1. Introduction

The particles composing the halos to be studied here are theoretical constructs; first imported from particle physics when it became clear that (assuming general relativity is valid) most of the matter in the Universe is invisible and that most of this material should be in non-baryonic form (assuming standard big bang nucleosynthesis is valid). What distinguished the Cold Dark Matter (CDM) particles from the host of other available options was their relatively small velocity dispersion at the time of matter-radiation equality. This meant that structure was not erased at the relevant scales. It is however precisely this property — the particles being cold — that gave rise to the host of problems associated with CDM theory at the kpc scale and below; dubbed the "core catastrophe" by Moore et al. (1999). These turn out to be mostly related to the large central concentration of the resulting halos.

Possible solutions were again sought in particle physics; warm dark matter and self-interacting dark matter being among the most popular. The former however was found to be inadequate in washing out the cusp (Colin, Avila-Rees & Valenzuela 2000), while in the latter, in general, the core catastrophe is replaced by a (more serious) gravothermal catastrophe (Kochanek & White 2000). The basic idea behind the interacting dark matter proposal is to transport energy to the inner region, causing it to expand. This does indeed happen, because these systems initially have temperature inversion. Once this is washed away however, a runaway thermal instability develops — with the core contracting

as it loses energy, while still getting hotter (see Lynden Bell 1998 for a recent review of this phenomenon).

Recently, we have proposed a two component model with one component (the CDM) always receiving energy and the other (baryonic) component always losing it. Moreover, we have shown that the CDM component's tendency to expand overcomes the effect of adiabatic contraction. The coupling between the two components is provided by dynamical friction — with the mechanism being efficient over timescales of the order of a Gyr, provided the Baryonic material is distributed in clumps of $> 0.01\%$ the total mass of the system (El-Zant, Shlosman & Hoffman 2001; ESH). The resulting halos have rotation curves that are well fit by those inferred from observations. The final baryonic distribution depends on the initial conditions (which determines the amount of binding energy stored in that component) and the relative magnitude of the dynamical friction to collision times — with the latter determining a natural termination of the process via collisions, fragmentation, star formation etc.

As opposed to the dark matter, a centrally concentrated baryonic density distribution is compatible with observations of galaxies — as in their bulge-black hole systems. Baryonic material also participates in electromagnetic and nuclear interactions, and therefore can do things that CDM cannot (e.g., form stars and participate in wind driven outflows). In this context, processes taking place at the kpc scale and below are coupled to the structure of dark matter at the 100 kpc scale and, through this, to the large scale structure of the Universe. We will show in this paper that there is a correlation between the rate of baryonic mass inflow resulting from the coupling with the dark matter component and the initial structure and subsequent evolution of the latter. First we briefly discuss the method, initial conditions and values of the parameters that are used.

2. Method, parameters and initial conditions

The method used here is described in ESH: Baryonic clumps suffer dynamical friction, described by the Chandrasekhar formula, and the energy lost is redistributed among the dark matter particles using a Monte Carlo technique. A system of 10^5 particles is divided into a 10^3 equal number bins. The energy lost by the gas particles of mass M and velocity $\mathbf{V}_M$ in a timestep Δt in a given bin

$$E_{lostbin} = \Sigma_{bin} M \left(\frac{d\mathbf{V_M}}{dt} . \mathbf{V}_M \right) \Delta t, \tag{1}$$

is gained as random kinetic energy by the halo particles in the same bin:

$$V_i \rightarrow V_i + F(y), \tag{2}$$

where F is a normal distribution of zero mean and variance

$$y = \sqrt{(2/3)E_{lostbin}/m_{bin}}, \tag{3}$$

and m_{bin} represents the CDM mass in a given bin. In the simulations presented here *both* the dark matter and baryonic components initially obey a Navarro, Frenk & White (1997) (NFW) density distribution:

$$\rho_i = \frac{\rho_s}{r(r_s + r)^2}. \tag{4}$$

The velocities are determined by solving the Jeans equation and are sampled from a Maxwellian distribution. The baryonic mass fraction was fixed at 10% of the total mass. The mass of a single baryonic lump was taken to be 0.1% the total mass of the system. The length and time units used take advantage of the "universal" (independent of mass) scaling of the NFW halos and are given by

$$[r] = 1.63 M_{DM}^{1/3} h^{-2/3} 10^{-4} \text{ kpc} \tag{5}$$

and

$$[t] = 0.97 h^{-1} \sqrt{M_{DM}/M_{tot}} \text{ Myr.} \tag{6}$$

3.   Results

Fig. 1 shows the time evolution of the baryonic mass distribution for three values of the NFW scaling parameter r_s that roughly span the allowed range found in simulations. The evolution is much more rapid when r_s is smaller: more *concentrated initial distributions evolve faster.* This is a result of the higher central density — leading to stronger DF coupling and shorter dynamical time. It is also evident that by the final time shown (corresponding to about a Gyr) most of the mass, originally within the inner 10 kpc or so, becomes concentrated near the center. In reality this overestimates the amount of mass inflow to the central region — since we neglect here effects due to collisions, star formation etc., which would regulate the central influx at high densities. In practice then one would expect, in addition to a large central mass component, the process to result in a corresponding bulge component, the prominence of which would depend on the efficiency of the above mechanisms. Different initial conditions for the baryonic component can also lead to very substantial reduction in central concentration (compare, e.g., with top right panel of Fig. 1 of ESH). Nevertheless it is clear that the processes described here can result in the buildup of central mass concentration, and the formation of a bulge-black hole component, whose structure and properties are dependent on the initial halo density distibution.

Since the initial evolution proceeds "inside out" — that is, with the higher density regions evolving at a faster rate — the halo profile is first affected in the inner regions. At this stage, when a core develops in the very central region but the structure at intermediate radii is not affected, the density profile was found to be fit by

$$\rho = \frac{C}{(r_c + r)(A + r)^2}. \tag{7}$$

The requirement that this equation fit the density at large radii fixes C. As halos evolve, this fit becomes a one-parameter fit, since it is found that best fits invariably have $r_c \sim A$. We take here the point in time where this happens to define the formation of a significant nearly constant density core. Since outputs are sampled every 200 time units, there is a certain coarse graining in our determination of this time. We find that this point is reached after 400 time units (about half a Gyr) for the cases of $r_s = 3$ and $r_s = 5$ and double that time for case of $r_s = 10$. The fits are shown in Fig. 2. Note that the final core radii correlate with the initial r_s. As explained in ESH this can lead to interesting correlations between the initial profiles obtained from simulations and the
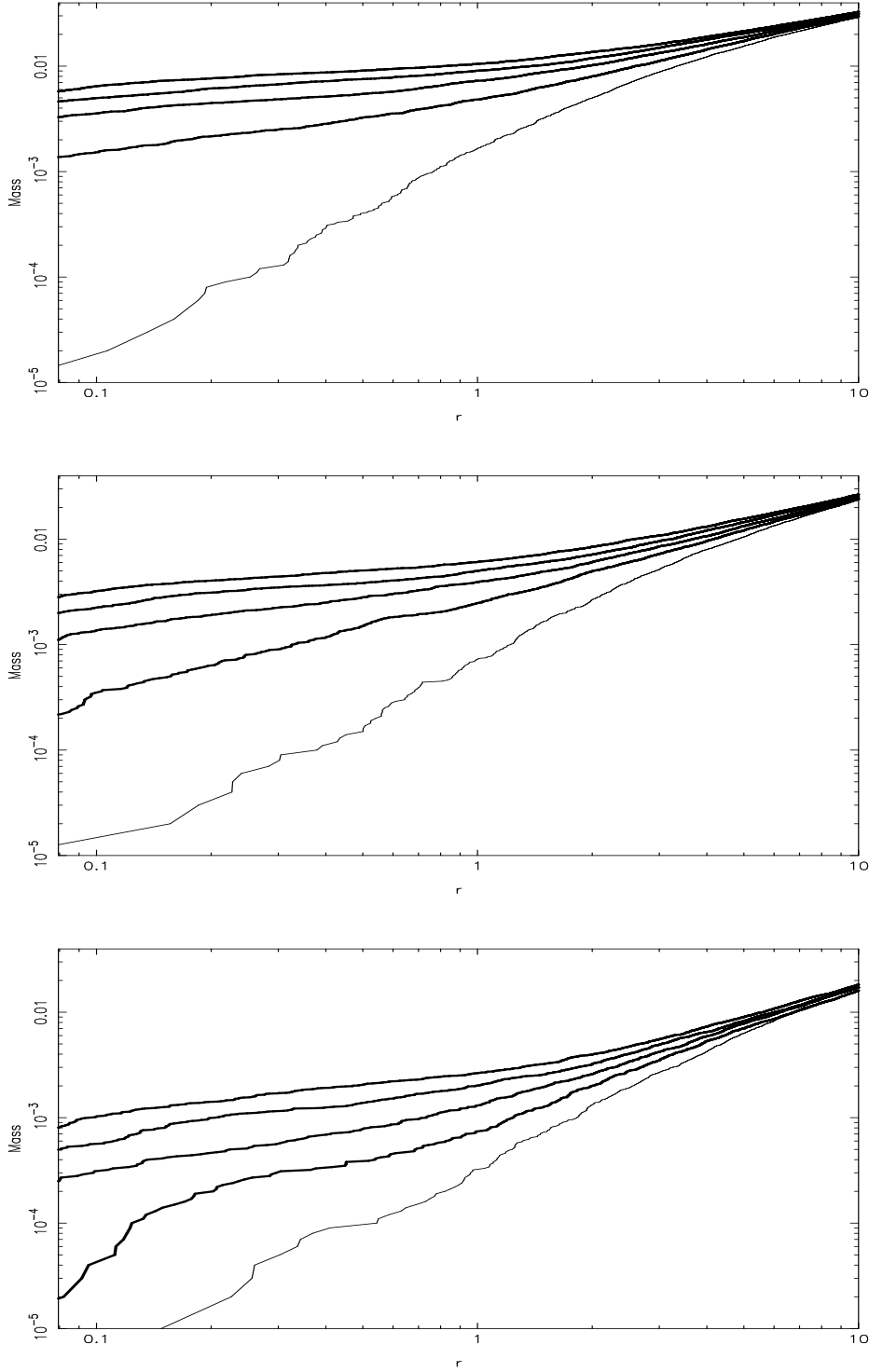
Figure 1. The baryonic mass distribution in systems with (from top to bottom) $r_s = 3, 5, 10$ (Eq. 4) at $T = 0, 200, 400, 800$ (inflow results in monotonous mass increase within a given radius). The total initial radius of the systems is 100 units. The total mass is taken as one unit, of which 0.1 is baryonic
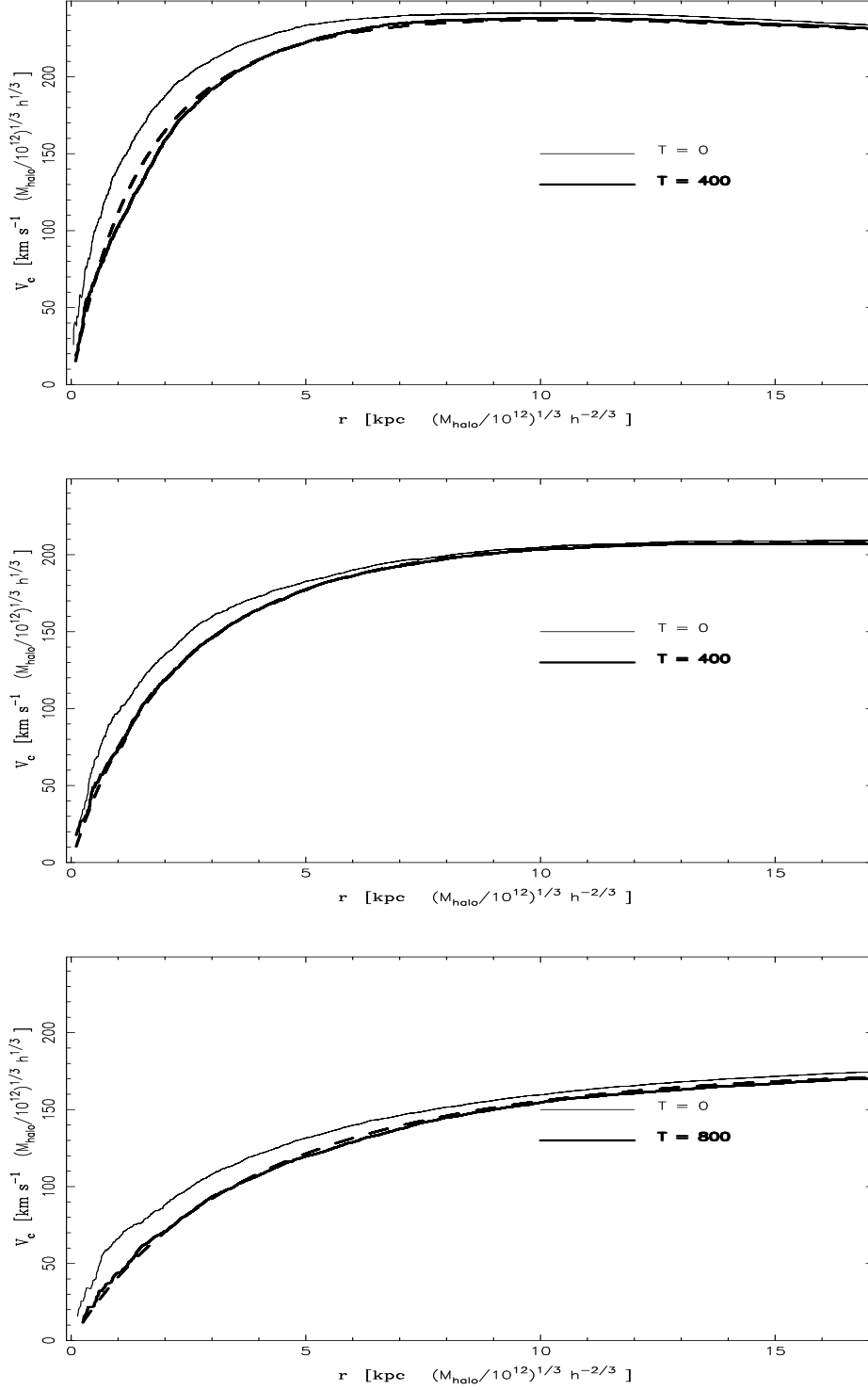
Figure 2.   Rotation curves of the CDM corresponding to systems of Fig. 1. Fits employ Eq. (7) with $A = 1.44$, $r_c = 1.43$ (top), $A = 2.11$, $r_c = 2.10$ (middle) and $A = 3.52$, $r_c = 3.62$.

final ones inferred from observations. As halos continue to evolve, their density structure at intermediate radii is modified and and is fit well by the "Burkert profile": $\rho = \frac{\rho_0}{r_0^2 + r^2}$. This happens within 2Gyr. The value of the Burkert core radii were also found to correlate with the initial NFW scale length.

4. Concluding remarks

The attempted solution of the apparent "core catastrophe" by coupling the baryonic and dark matter components via dynamical friction, gives rise to interesting coupling between baryonic structural properties at the kpc scale and below and the dark matter distribution on the 10 kpc scale and above. In this model, the baryonic component is clumpy, as is genrally expected during galaxy formation (e.g., Silk & Norman 1981), but in contrast with many calculations where a smooth baryonic component has been assumed for the sake of simplicity. As a result, energy is pumped into the halo and it "puffs up", as the expanding tendency resulting from the *energy input overcomes the competing effect of adiabatic contraction.* At the same time, the baryonic material loses energy and becomes more centrally concentrated. This material may participate in the formation of bulge-central mass component. The details of this process are not studied here, since we do not model effects of collisions and star formation that will eventually dominate the evolution of the clumpy gaseous component, and determine the relative efficiency of formation of the bulge and the central mass. Nevertheless, it is clear that *the rate at which this takes place depends on the dark matter halo's initial concentration — with more concentrated halos being more efficient in fueling central baryonic concentrations.* The final halo core radius also depends on the initial halo scale length. Here we have used the NFW profile for the initial conditions, whereas the central density decreases as $1/r$, and the scale length determines a turnoff radius beyond which the density profile tends to $\rho \propto 1/r^3$. The results presented suggest that the mechanisms described above are likely to be more efficient if CDM halos are initially more concentrated than in the NFW picture (i.e., if the central density decreases as $\rho \propto 1/r^\gamma$, $\gamma > 1$ as inferred from the higher resolution simulations).

References

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